Pyrolysis and gasification characteristics of Pongamia residue (de-oiled cake) using thermogravimetry and downdraft gasifier

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HIGHLIGHTS

- Thermal decomposition of the Pongamia de-oiled cake occurs in three stages.
- At low heating rate (10 °C/min), the higher mass loss rate was achieved.
- The minimum activation energy of 162 kJ/mol is required for complete gasification.
- Gasification efficiency of the de-oiled cake pellets was 65% as compared to the wood (84%).
- Pongamia de-oiled cake pellets of 17 mm and 11.5 mm diameter are not suitable for efficient and problem free gasification.

ARTICLE INFO

ABSTRACT

General research in the area of gasification of biomass includes either study of kinetics of pyrolysis or gasification of selected bios mass. A combined kinetic investigation of the pyrolysis of the de-oiled cake at various heating rates along with gasification of pelletized biomass was carried out in the present work. It is found that the thermal decomposition of de-oiled cake occurs in three stages. Most of the material decomposed (∼60%) in stage-II between 166 °C and 480 °C. Kinetic parameters were obtained by differential and FWO methods. The activation energies are obtained in the range of 68.8—177.9 kJ/mol and 41.3—161.8 kJ/mol by differential method and FWO methods respectively. These results were consistent with those obtained in the literature. The TGA results show that a minimum heating rate (10 °C/min) and minimum activation energy (162 kJ/mol) is required for pyrolysis and gasification of de-oiled cake. The results of TGA were used to select the suitable size of pellets. De-oiled cake pellets of 17 mm and 11.5 mm diameter and length in the range of 10—68 mm were prepared and gasified in a 20 kWe downdraft wood gasifier. The complete gasification of pellets could not be achieved because of less porosity and more elasticity and presence of larger thermal gradient within the pellets. Pongamia de-oiled cake pellets of 17 mm and 11.5 mm diameters are not suitable for gasification.

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1. Introduction

In many developing countries, the fraction of biomass energy consumed ranges from 40% to 50% since the countries have large agriculture and forest area [1]. India, one of the leading developing countries, has huge potential of the biomass resources consisting about 321 million tonnes per year in agro-ecological zones [2]. In different parts of India, forest oilseeds like *Madhuca indica*, *Pongamia pinnata*, *Shorea robusta*, *Mallotusphilip pines*, *Mesua ferra*, *Garcinia indica*, are available with good tree density. Oil from these

species is being used for biodiesel production. This biodiesel can be used for generating electricity using diesel engine generators [3&4].

Pongamia pinnata is a forest tree belonging to the family Leguminosae, grown in all parts of India, particularly in Tamil Nadu, Andhra Pradesh and Karnataka, for its ecological advantages. The seed contains 27—39% oil, 20—30% protein and a group of furanoflavonoids that constitute 5—6% by weight of the oil. The estimated production of seed is nearly 0.11 million tonnes per annum in India. The projected production of oil is nearly 30,000 tonnes per annum, at present. The oil is extracted by expellers, leaving 15—20% of residual oil in the cake. The cake, which is bitter and pungent, is used (in small quantity) as manure, fungicide and insecticide. Although the cake is rich in proteins, it is unpalatable and toxic due to the presence of karanjin, pongamol and an unusual amino acid, glabrin. However, raw cake is not normally used as feed for animals

and livestock due to its toxicity [5]. The Pongamia de-oiled cake, a solid residue that is usually discarded after extraction of oil from the seeds, contains lignin and cellulose in varying ratios. Moreover, due to increasing demand of biodiesel, the quantity of de-oiled cakes has increased tremendously and about 2 tonnes of oil cake is discarded as a waste for every tonne of biodiesel produced. One of the major problems associated with this increase would be the disposal of shells and the de-oiled cake after expelling oil from the seeds [6].

Pyrolysis could be a promising residue management option to convert the waste of shells and de-oiled cake to fuel products that are easier to transport, store, handle, and utilize. Pyrolysis is one example of thermochemical conversion of biomass [7]. However, pyrolysis is an extremely complex process; it generally goes through a series of reactions and can be influenced by many factors. This process yields liquid oil, solid charcoal, and gases in different proportions, depending on the temperature, heating rate, reactor type, and biomass particle size [8–11].

A few major attractions of gasification are that it can convert waste or low-priced fuels, such as biomass, coal, and petcoke, into high-value chemicals. Biomass holds great appeal for industries and businesses; especially in the energy sector [12]. Biomass gasification is the latest generation of biomass energy conversion processes and is being used to improve the efficiency and to reduce the investment costs of biomass electricity generation through the use gas turbine technology [13].

Many types of gasifiers were reported in the past and they can be broadly categorized based on the basis of the flow direction of air/gas in a gasification reactor. The gasifiers are classified as up draught, downdraught and cross-draught gasifiers. In all these gasifiers, biomass flows downwards by gravity. In up draught gasifier, the flow of air and gas is upwards direction. If the flow of air and gas is downwards, it is downdraught gasifier. While in case of a cross-draught gasifier, the air and gas flows horizontally, perpendicular to the flow direction of biomass [14].

Lenis et al. [16] reported a statistical repeatability study of the main biomass gasification process parameters in a laboratory-scale fixed bed downdraft gasifier on batch operation by using analysis of variance. They suggested that the solid fuel distribution inside the bed was always different, leading to variations in the process parameters.

Numerous investigations on different types of biomass species have been carried out in the past on downdraft gasification systems. The briquetted leather residues (nominal size of 70 × 50 mm and bulk density of 537.30 kg/m^3) were successfully gasified in a throated 10 kWe downdraft gasifier. The temperatures of various zones were measured. The oxidation, pyrolysis, and drying zone temperatures were respectively measured around, 1050 °C, 530 °C, and 290 °C. The large briquette sizes of the leather residues occasionally formed bridging in the throat zone of the gasifier [17]. Vera et al. [18] carried out an experimental and modeling study of a downdraft gasifier and gas engine fueled with olive oil industry wastes. The gasifier is fed with olive mill wastes: small branches and leaves and olive pits. The producer gas generated from crushed olive pits has calorific value of 5.1 MJ/kg and 3.7 MJ/kg for small branches and leaves. In this study; they found that an olive pit has good potential for combined heat and power plant. The small branches and leaves may be used in combustion application but not for gasification.

In view of above context, the objective of present work is focused on the study of Pongamia de-oiled cake as an alternative source of energy through pyrolysis and gasification. It is not possible to use de-oiled cake directly in gasifier. The better option is to pelletize the de-oiled cake. The producer gas generated from the pellets can be used for heat and or power generation for rural areas.

2. Experimental setup and methodology

2.1. Feedstock characterization

In the present work, the Pongamia de-oiled cake was collected from the oil processing industry in the state of Madhya Pradesh, India. The Pongamia de-oiled cake was air dried and crushed and sieved to produce the particles with the size less than 297 microns.

The physical and chemical properties (proximate and ultimate analysis) of the Pongamia de-oiled cake are given in Table 1. The de-oiled cake pellets (DOCP) have a higher bulk density (489 kg/m^3) when compared to the Pongamia pure shells (146 kg/m^3). DOCP has slightly higher calorific value and carbon content when compared to the Pongamia shells as shown in Table 1. The important properties of Pongamia shells and DOCP in comparison with wood are listed in Table 1.

2.2. Experimental conditions for pyrolysis

The Perkin–Elmer TGA-7 thermogravimetric analyzer was used to analyze the thermal characteristics of the Pongamia residue (de-oiled cake). The samples of de-oiled cake were pyrolyzed with heating rates of 10, 15, 20 and 30 °C/min respectively in the temperature range (TR) from room temperature to 700 °C. Nitrogen was used as a carrier gas with a flow rate of 20 ml/min throughout the experiment. The thermogravimetric analysis was carried out in order to obtain kinetic parameters of the samples.

2.3. Pelletization of Pongamia de-oiled cake

The pelletization of de-oiled cake was carried out in two steps, namely crushing of raw material and pelletization. A special hammer mill was used for crushing of raw material. An existing hammer mill with 32 numbers of hammers and screen size of 8 mm holes was used to crush the de-oiled cake into fine powder. A mixture of fine powder, water and bonding agent (if required) was prepared for production of pellets. A pelletizing machine with a flat die was used to make the pellets. The flat die has total 33 holes of 18 mm diameter with a working width of 77.5 mm and effective compression length of 45 mm, total thickness 53 mm and has a maximum output of 100 kg per hour. The power consumption of the pelletization machine was measured to be in the range of 6.2–6.9 kW at full load condition.

Another die plate of 12 mm hole diameter was fabricated. All other dimensions of the die plates were the same as the older die plate. The purpose of fabrication of this die plate was to study the effect of hole diameter on the bulk density of pellets, length of pellets, thermal properties of the pellets and quality of the producer gas generated with smaller diameter pellets.

The Pongamia de-oiled cake pellets (DOCP) of 17 mm and 11.5 mm diameters were produced as shown in Figs. 1 and 2 respectively. These pellets were air dried and stored in the 15 kg plastic bags. The bulk density of pellets of 17 mm and 11.5 mm diameters was measured to be 489 kg/m^3 and 502 kg/m^3 respectively. The length of DOCP was in the range of 10–68 mm. The pellets of 17 mm diameter were less porous with very smooth surface finish and relatively more plasticity. The surface finish of pellets of 11.5 mm diameter was rough as compared to the pellets of 17 mm diameter.

The biomass that could be used as the feedstock in the existing downdraft gasifier are different species of wood whose bulk density is above 175 kg/m^3 and ash content is less than 2%. The bulk density of hardwood and softwood are 330 kg/m^3 and 250 kg/m^3 respectively [21].

Table 1
Proximate analysis (% wet basis) and ultimate analysis (% dry basis) of Pongamia de-oiled cake.

Sample	Proximate analysis (% wet basis)[b]				Ultimate analysis (% dry basis)[c]					
	Moisture (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	C (%)	H (%)	N (%)	O[d] (%)	Bulk density (kg/m^3)	Calorific value (MJ/kg)
De-oiled cake[a]	12.00	71.21	11.71	5.08	47.11	5.63	0.27	41.91	489	17.65
Pongamia shells[a]	11.61	70.83	11.86	5.70	46.02	5.58	0.23	42.46	146	16.81
Wood[b,c]	10–15	70–80	15–20	1–3	52.30	5.20	0.50	42.00	330	18.50

[a] Present study.
[b] [19].
[c] [20].
[d] By difference.

2.4. Downdraft wood gasifier

Fig. 3 shows an overall view of the 20 kWe downdraft gasifier system [22] which is used in the present study. DOCPs in the reactor were ignited by holding a flame in the form of wick near each air nozzle. After 10–15 min of operation, the product gas (producer gas) was ignited in the burner. The composition of the producer gas generated from the pellets gasification was measured by using a gas chromatograph unit.

The temperature variation in various zones (preheating, drying, pyrolysis, oxidation and reduction zones) of the gasifier was measured by using S-type thermocouples. The thermocouples were specially manufactured for various lengths and stainless steel was used as holding tube. The heights of preheating, drying, pyrolysis, oxidation and reduction zone were 1000, 1600, 1670, 1840 and 2010 mm respectively from the top of the gasifier. The location and position of the thermocouples were fixed for each zone of the gasifier. Eight channels Data Logger with computer interface was used for temperature recording. Thermocouples were inserted from the top of the gasifier before charging the gasifier. K-type thermocouples can measure the temperature in the range of 0–1050 °C. If the temperature is higher than this range then the thermocouples may loses linearity in measurement.

The various zones of the downdraft gasifier are shown in Fig. 4. The reactions which take place in the oxidation zone are exothermic. The reaction which takes place in the reduction zones is Boudouard reaction, water gas reaction, water shift reaction and methane formation reaction. Precise sequence of reactions is very complex and their relative importance depends on the fuel type and gasifier design. The detailed description of the air gasification process in the downdraft gasifiers are reported in the several published literature [15].

3. Results and discussions

3.1. TGA results for Pongamia de-oiled cake

The mass loss curves for Pongamia de-oiled cake for heating rates (HR) of 10, 15, 20, 30 °C/min are shown in Fig. 5. These plots show the trend of these curves with increasing heating rates for Pongamia de-oiled cake. The TGA curves show that there is an initial loss of moisture from the samples starting from room temperature and continuing up to about 166 °C. The nature of a TGA curve gives a clear indication of number of stages of the thermal degradation. The first mass loss occurs in stage-I from room temperature to 166 °C, the second mass loss occur between 166 °C and 480 °C for all the samples in stage-II, whereas third mass loss for Pongamia de-oiled cake it is extended up to 700 °C in stage-III.

Differential Thermogravimetric Analysis curves (DTGA) as shown in Fig. 6, which shows a major mass loss peak, followed by a second peak. The second peak is small as compared to the first peak. The values of temperature range (TR) and peak temperature (PT) shifts to higher values upon increasing the heating rate from 10

Fig. 1. Photograph of DOCP (17 mm).

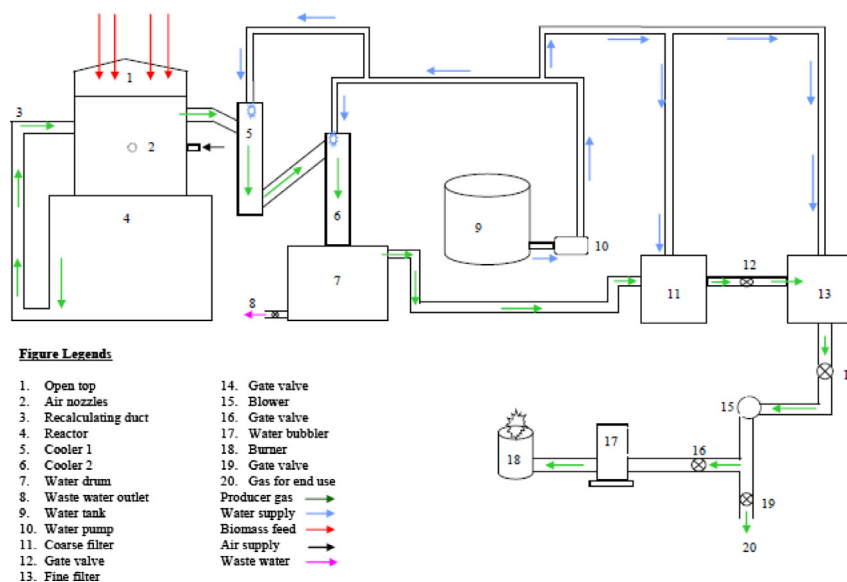**Fig. 2.** Photograph of DOCP (11.5 mm).

Fig. 3. Overall view of the gasifier setup.

to 30 °C/min. It also shows an increasing trend in the maximum rate of mass loss with increasing heating rate. The amount of solid residue left unconverted at 700 °C increases by 87%, upon increasing heating rate from 10 °C/min to 30 °C/min.

The pyrolysis characteristics and DTGA (in %/°C) curves of de-oiled cake is shown in Fig. 7. The pyrolysis of de-oiled cake starts at 166 °C, its mass loss rate (in %/°C) increases sharply with increase in temperature and reaches its maximum value at 382 °C for heating rate of 30 °C/min. The decomposition of de-oiled cake in stage-II is linear up to the maximum value of the first DTGA peaks (Fig. 7). This is due to decomposition of cellulose and hemicellulose in the temperature range of 220–400 °C. For same temperature, the mass loss rates are similar for heating rates 10, 15 and 20 °C/min as compared to the heating rate 30 °C/min. Though the mass loss rate is higher for heating rate 30 °C/min as compared to heating rates 10–20 °C/min, the overall conversion is lower (Fig. 6). The

maximum decomposition (more than 60%) of de-oiled cake sample takes place in the stage-II. The second DTGA peaks (in the stage-III) are quite visible; it is due to the decomposition of lignin at temperatures above 480 °C. Yang et al. [24] suggested that at higher temperature (above 350 °C) second peak appears due to lignin decomposition for palm oil waste. It has been observed that in the stage-III, where temperature is above 500 °C, the mass loss rate is lower for heating rate 30 °C/min as compared to heating rates 10–20 °C/min. The second DTGA peaks (%/°C) are smaller as compare to the first DTGA peaks. The amount of solid residue (char) at the end of the pyrolysis process of de-oiled cake is similar for low heating rates (10–20 °C/min) but high at heating rate of 30 °C/min. At higher heating rate (more than 20 °C/min), there may be a large thermal gradient within the sample particle and more residence time requirements for pyrolysis in the stage-III when temperature is above 480 °C. TGA and DTGA results for de-oiled cake pyrolysis shows that the heating rate (20 °C/min) is better as compared to the high heating rate (30 °C/min) as discussed above.

A similar trend of mass loss was reported by Gottipati and Mishra [6]. In their study, the first mass loss had occurred approximately between 230 °C and 350 °C for all the samples, and second mass loss occurred between 350 °C and 580 °C for Ponga-mia cake, whereas for Madhuca and Jatropha oil cakes it had extended up to 650 °C. Parekh et al. [25] reported an increase in the
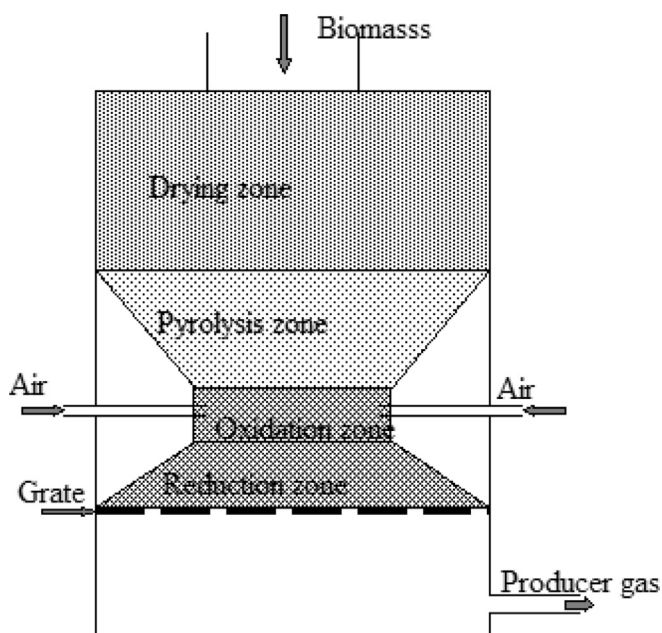

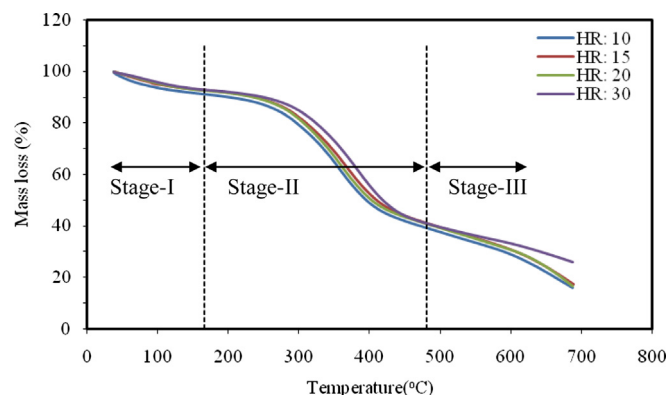**Fig. 4.** Schematic diagram of a downdraft gasifier.

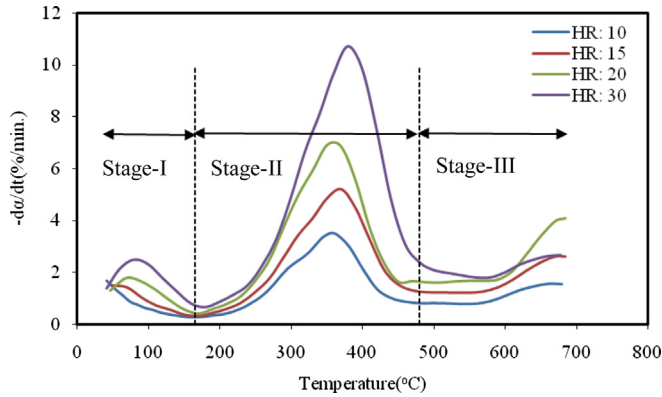**Fig. 5.** Comparison of TGA curves for Pongamia de-oiled cake at different HR.

Fig. 6. Comparison of DTGA curves for Pongamia de-oiled cake at different HR.

Fig. 8. Plots of ln(dα/dt) Vs 1/T using differential method (Eq. (1)).

amount of solid residue from 11.44% to 26.72% for Jatropha cake and from 6.8% to 11.31% for Karanja cake when the heating rate was increased from 5 to 20 °C/min at 900 °C.

3.2. Pyrolysis kinetic parameters from the thermogravimetric data

The pyrolysis kinetic parameters from the thermogravimetric data was calculated by differential method and the Flynn–Wall–Ozawa (FWO) Method as discussed below:

3.2.1. The differential method
The differential method was used to obtain the pyrolysis kinetic parameters from the thermogravimetric data. Thus, the kinetics of most reactions under non-isothermal conditions can be summarized by the following general equation [26].

$$\ln\left(\frac{d\alpha}{dt}\right) = \ln\left[\left(\frac{1-\alpha}{1-X_C}\right)A\right] - \frac{E}{RT} \tag{1}$$

where:

    A pre-exponential factor, 1/s
    T pyrolysis temperature, K
    E activation energy, kJ/mol
    R universal gas constant = 8.314 J g/mol K
    X_c char fraction
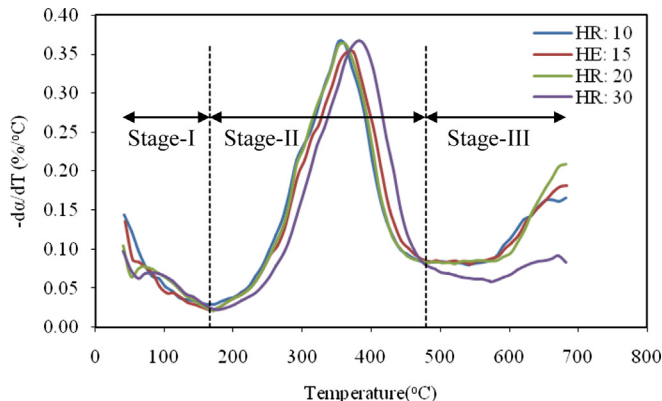   α percent conversion of samples
    t pyrolysis time, s

Apparent activation energy, E, is determined from the relationship between ln(dα/dt) and 1/T from Eq. (1). Thus, a family of parallel straight lines of slope −E/R can be obtained, from which the apparent activation energy (E) corresponding to the selected conversion can be obtained.

Plots of ln(dα/dt) versus 1/T according to differential method using Eq. (1) is shown in Fig. 8. The family of straight lines was used to calculate the apparent activation energy for the Pongamia de-oiled cake.

3.2.2. The Flynn–Wall–Ozawa (FWO) method
The Flynn–Wall–Ozawa (FWO method) is a model-free method [27] which involves measuring the temperatures corresponding to fixed values of α (conversion fraction) from experiments at different heating rates, β, where β is given by Eq. (2), and plotting log β vs. 1000/T.

$$\log\beta = \log\left[\frac{AE}{g(\alpha)R}\right] - 2.315 - 0.457\frac{E}{RT} \tag{2}$$

The slope of such a plot gives the value of −E/R. If E varies with α, the results should be interpreted in terms of multi-step reaction mechanism [28].

Plots of log β versus 1000/T according to Flynn–Wall–Ozawa (FWO) method using Eq. (2) is shown in Fig. 9. The apparent activation energies were calculated by using Eqs. (1) and (2) at various percentages of conversion.

The variation of activation energies as a function of percentage conversion for Pongamia de-oiled cake is shown in Fig. 10. The range of activation energies of the samples increases with increasing conversion. The activation energy of de-oiled cake sharply decreased from 50% conversion on ward. This region corresponds to the second mass loss rate in the DTGA curves (in stage-III as shown in Fig. 7.) due
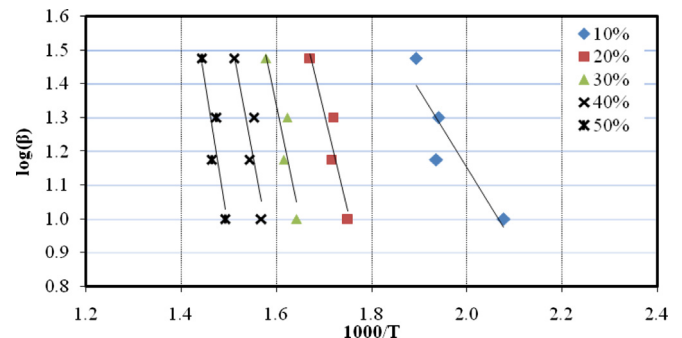

Fig. 7. Comparison of DTGA curves for Pongamia de-oiled cake at different HR.

Fig. 9. Plots of log β Vs 1000/T using the Flynn–Wall–Ozawa (FWO) method (Eq. (2)).
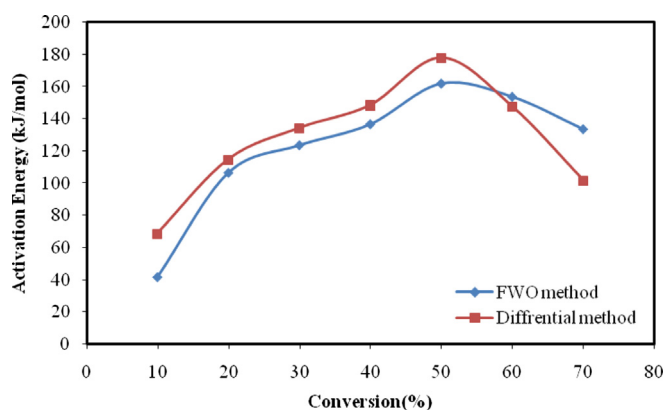
Fig. 10. Calculated activation energies at different conversions for pyrolysis of Pongamia de-oiled cake by using FWO and differential methods.

to further slow thermal decomposition of lignin component of de-oiled cake. The activation energies and the pre-exponential factors are obtained in the range of 68.8–177.9 kJ/mol and $10^5–10^{12}$ min^{-1} respectively by differential method. The activation energies are obtained by FWO method in the range of 41.3–161.8 kJ/mol. It is observed that activation energy obtained by the two methods is quite similar. The activation energy of hardwood lignin was obtained by nonisothermal method in the range of 33–284 kJ/mol at a heating rate of 15 °C/min [26].The activation energy of the rice husk, olive cake and cacao shells were obtained by Friedman, Flynn and Wall, Kissinger models 150, 141.6 and 94.6 kJ/mol at low heating rates (5–20 K/min) [29].The kinetic parameters obtained for de-oiled cake from thermogravimetric data shows that the activation energy is comparable to various biomass materials as reported in the literature. Maximum activation energy of 162 kJ/mol is required for complete gasification of the Pongamia de-oiled cake.

3.3. Gasification of Pongamia de-oiled cake pellets (17 mm diameter)

The gasifier was run on DOCP in suction blower mode. DOCP with size of 17 mm diameter and length in the range of 10–68 mm with moisture content of 12% were loaded into the reactor. Pellets were ignited by using wick near the each air nozzles as discussed in Section 2.4. It was observed that after 10–15 min of flaring, a blue flame was obtained which showed a good quality of the producer gas. The average temperatures in the preheating and drying zones were nearly same at 32 °C and 37 °C respectively. The maximum temperatures in the oxidation and the reduction zones were found to be 1092 °C and 936 °C respectively. The temperature variation in

Fig. 11. Temperature variations in various zones of the gasifier with time, after 15 min of flaring.

the various zones of the gasifier with time for two air nozzles opened and top opened condition is shown in Fig. 11. The temperature of the pyrolysis zone was almost similar to that of oxidation zone. During gasification of pellets; it was found that there was no agglomeration and blocking of the gasifier. It was also observed that the complete gasification of DOCP could not be achieved because of larger diameter of pellets. The possible reasons for incomplete gasification of DOCP are less porosity and relatively more plasticity with very smooth surface finish and the presence of larger thermal gradients within the pellets. The center line temperature of the pellets is low even though a high local temperature (average temperature in the reduction zone was 735 °C as shown in Fig. 11) is reached. The residence time and heating rate also affects the gasification process. At high heating rates, the mass loss rate is lower for temperature above 480 °C as shown in Fig. 6. The quality of the producer gas is low as compared to the producer gas generated from the wood. The optimized operating conditions of gasifier are not suitable for DOCP with 17 mm diameter for gasification. Then it was decided to operate the gasifier with smaller diameter pellets (11.5 mm). Sharma [23] had reported that the temperatures in the oxidation and the reduction zones were 997 °C and 672 °C respectively for the same downdraft gasifier using softwood. He also used the same location for temperature measurement in the oxidation and reduction zones but he used K-type thermocouples with a different arrangement for temperature measurements in various zones for three air nozzles opened and top opened condition.

A gas chromatograph unit (Model GC7720) was used to measure the producer gas composition. Two samples of producer gas were collected into Tedlar bags of 0.5-L capacity each. Each collected sample was analyzed twice using the gas chromatograph unit. The analyzed gases were CO, H_2 CH_4, CO_2 and N_2. The composition of producer gas generated from DOCP gasification is presented in Table 2. The quality of the producer gas (calorific value) was also not good as compared to the wood gasification for same operating conditions of the gasifier. The composition of the producer gas was not varying much during gasification of DOCP(% deviation is very small) H_2 = 7.44%(±0.135%), CO = 10.93%(±0.334%), CH_4 = 1.09%(±0.186%), CO_2 = 9.20%(±0.336%), N_2 = 71.44%(±0.095%).

A higher temperature (above 850 °C) in the oxidation zone helps in easy cracking of tar. This results in low tar content in the producer gas [30]. The best gasification conditions are those in which a high local temperature is reached, while keeping the fuel in excess, and all biomass hydrocarbons react (there is no unburned material in form of tars or in the remaining char), but avoiding the conversion to inert substances such as CO_2 and H_2O [31].

3.3.1. Calculations for operating parameters of the gasifier

Assuming chemical properties of biomass are Carbon, Hydrogen, Oxygen, and Nitrogen, chemical reaction equation for DOCP gasification can be written as:
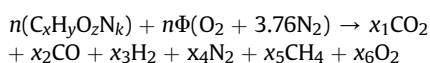
$$n(C_xH_yO_zN_k) + n\Phi(O_2 + 3.76N_2) \rightarrow x_1CO_2 + x_2CO + x_3H_2 + x_4N_2 + x_5CH_4 + x_6O_2$$

Table 2
Composition of producer gas from Pongamia de-oiled cake pellets.

Biomass material	Producer gas composition (%)				
	H_2	CO	CH_4	CO_2	N_2
DOCP[a]	7.44	10.93	1.09	9.10	71.44
Wood[b]	14.95	17.03	1.02	11.46	55.55

[a] Present study.
[b] [19].
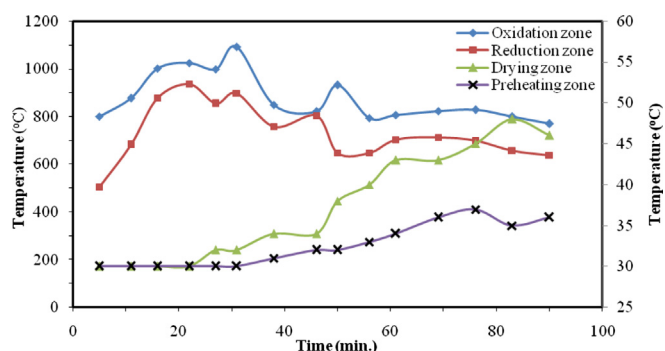
Using ultimate analysis of de-oiled cake from Table 2 and Molecular Weight of Carbon, Hydrogen, Oxygen and Nitrogen to calculate x, y, z and k:

3.3.1.1. Operating parameters of gasifier

1. Gas flow rate

Gas flow rate through venturi as given by I.I.Sc Operation & Maintenance Manual is calculated using equation;

$$\dot{m}_g = 3.3\sqrt{\Delta h_w} + 1.755 \tag{3}$$

where: Δh_w = Manometers differential height (mm)

2. Air–Fuel ratio

Calculation on basis of 100 kg fuel.

$$(A/F)_m = \frac{4.76 \times \phi \times MW_{air}}{100} \tag{4}$$

where: MW_{air} = Molecular weight of air

3. Calorific value of producer gas

Calculation for calorific value of producer gas, required calorific value of each compound is presented in Table 3. From Iyer et al. [32] the data as follows:

$$Q_{CV_g} = \frac{(x_2 \cdot CV)_{CO} + (x_3 \cdot CV)_{H_2} + (x_5 \cdot CV)_{CH_4}}{100} \tag{5}$$

4. Mass of producer gas generated per kg of DOCP

The total mass of Pongamia residue used to produce 100 kmol of dry producer gas is $100 \times n$ kg. Therefore, mass of dry producer gas produced per kg of Pongamia residue is calculated using following formula:

$$\dot{m}_g = \frac{\Sigma x_i MW_i}{100 \times n} \tag{6}$$

where;

$$\Sigma x_i MW_i = (x_1 \cdot MW)_{CO_2} + (x_2 \cdot MW)_{CO} + (x_3 \cdot MW)_{H_2} + (x_4 \cdot MW)_{N_2} + (x_5 \cdot MW)_{CH_4}$$

5. Density of producer gas

$$\rho_g = \frac{P_{atm}}{R_g \cdot T} \tag{7}$$

where:

P_{atm} = atmospheric pressure = 101,325 N/m^2
R_g = producer gas constant = 8315J/kmol $-$ K/MW$_g$
T = ambient temperature (303 K)

Table 3
Calorific value of compounds.

Compound	CV (MJ/Nm^3)
CO$_2$	0
CO	12.71
H$_2$	12.78
N$_2$	0
CH$_4$	39.76

6. Energy release per kg of DOCP

$$E_g = \frac{\dot{m}_g \cdot Q_{CV_g}}{\rho_g} \tag{8}$$

7. The gasification efficiency or Coefficient of thermal conversion

Assuming 100% thermal conversion of feedstock and ambient temperature 303 K at 1 atm, coefficient of thermal conversion become:

$$C_{th} = \frac{E_g \times (273/303)}{Q_{CV_{DOCP}}} \tag{9}$$

Table 4 shows the parameters of the biomass like calorific value of producer gas, mass of producer gas generated per kg of biomass, energy released per kg of biomass and coefficient of thermal conversion of biomass gasification. The parameters presented in Table 4 were obtained for gasification of wood [19] whereas the data for DOCP were obtained in the present study. The gas flow rate of producer gas generated from DOCP was higher than that obtained during the wood gasification in the gasifier with two nozzles open, with 16 cm diameter of the conical grate.

It was observed that the calorific value of the producer gas generated from DOCP was 2.77 MJ/Nm^3. The energy release per kg of DOCP was lower for DOCP (12.81 MJ/kg DOCP) than the wood gasification (15.01 MJ/kg wood). The gasification efficiency or the coefficient of thermal conversion (defined as the ratio of energy release per kg of biomass to the energy contained in biomass) for wood and DOCP with 17 mm diameter was calculated to be 0.84 and 0.65 respectively.

3.4. Gasification of Pongamia de-oiled cake pellets (11.5 mm diameter)

Pellets with 11.5 mm diameter were loaded in the gasifier and the same operating procedure was followed. After 10–15 min of operation, it was not possible to generate producer gas because of the choking of the gasifier. Pellets were agglomerated and formed lumps in the; reactor and this result in the choking of the gasifier. The less porosity, low thermal gradient within the pellets and rough surface of DOCP with 11.5 mm diameter (as shown in Fig. 2) lead to incomplete gasification. This results in the agglomeration and lumps formation in the rector. The quality of the producer gas (heating value) generated with these pellets was not obtained. Therefore it was decided not to operate the gasifier with 11.5 mm diameter de-oiled cake pellets.

Table 4
Parameters of producer gas calculated for biomass gasification in downdraft wood gasifier.

Parameters	Wood[a]	DOCP[b]
Gas flow rate (g/s)	9.62	14.10
Mole of biomass (n)	7.3	5.38
Mole of air (Φ)	2.01	3.53
Air–Fuel ratio stoichiometric ($A/F)_s$	2.77	4.84
Calorific value of gas Q_{CV_g} (MJ/Nm^3)	4.48	2.77
Mass of gas generated m_g (kg of gas/kg biomass)	3.54	5.09
Molecular Wt. of gas MW$_g$	25.82	27.39
Density of gas ρ_g (kg/m^3)	1.06	1.07
Energy released per kg of biomass E_g (MJ/kg biomass)	15.01	12.81
Coefficient of thermal conversion (C_{th})	0.84	0.65

[a] [19].
[b] Present study.

4. Conclusion

Kinetic tests on pyrolysis of Pongamia de-oiled cake were carried out using a thermogravimetric analysis technique at the heating rate of 10, 15, 20, 30 °C/min. The thermal decomposition of de-oiled cake occurs in three stages, in stage-I moisture evolution and devolatization occurs and in stage-II & III pyrolysis take place. As shown in Fig. 6, the stage-II is linear up to the maximum value of the first DTGA peaks due to decomposition of cellulose and hemicellulose in the temperature range of 220–400 °C. The mass loss rates are similar for low heating rates (10–20 °C/min) as compared to the heating rate 30 °C/min. The maximum decomposition (more than 60%) of de-oiled cake sample takes place in the stage-II. The second DTGA peaks (in the stage-III) are due to the decomposition of lignin at temperatures above 480 °C.The activation energies are obtained in the range of 68.8–177.9 kJ/mol and 41.3–161.8 kJ/mol by differential method and FWO methods respectively. These results (kinetic parameters) were consistent with those obtained in the literature. The de-oiled cake pellets with 17 mm and 11.5 mm diameter were gasified in the downdraft gasifier for optimized operating condition. The gasification efficiency was 65% for 17 mm diameter pellets which is lower than that of wood gasification which was 84%. The calorific value of producer gas generated by pellets was 2.77 MJ/Nm^3. It was observed that the complete gasification of the pellets (17 mm diameter) could not be achieved because of less porosity and more plasticity as well as larger thermal gradient within the pellets. During gasification of 11.5 mm diameter pellets, it was observed that the pellets have agglomerated and form lumps in the gasifier. This results in the choking of the gasifier. Pongamia de-oiled cake pellets of 17 mm and 11.5 mm diameters are not suitable for efficient and problem free gasification in the downdraft gasifier.

Acknowledgements

References

[1] A. Gani, I. Naruse, Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass, Renew. Energy 32 (2007) 649–661.

[2] P. Sudha, N.H. Ravindranath, Land availability and biomass production potential in India, Biomass Bioenerg. 16 (1999) 207–221.

[3] N.V. Deshpande, N.W. Kale, S.J. Deshmukh, A study on biogas generation from Mahua (_Madhuca indica_) and Hingan (_Balanites aegyaptiaca_) oil seedcake, Energy Sustain. Dev. 16 (2012) 363–367.

[4] R.B. Hiremath, B. Kumar, P. Balachandra, N.H. Ravindranath, B.N. Raghunandan, Decentralized renewable energy: scope, relevance and applications in the Indian context, Energy Sustain. Dev. 13 (2009) 4–10.

[5] B.J. Vinay, T.C. Sindhu Kanya, Effect of detoxification on the functional and nutritional quality of proteins of Karanja seed meal, Food Chem. 106 (2008) 77–84.

[6] R. Gottipati, S. Mishra, A kinetic study on pyrolysis and combustion characteristics of oil cakes: effect of cellulose and lignin content, J. Fuel Chem. Technol. 39 (4) (2011) 265–270.

[7] V. Sricharoenchaikul, D. Atong, Thermal decomposition study on Jatropha curcas L. waste using TGA and fixed bed reactor, J. Anal. Appl. Pyrolysis 85 (2009) 155–162.

[8] A. Demirbas, Biomass resource facilities and biomass conversion processing for fuel and chemicals, Energy Convers. Manag. 42 (2001) 1357–1378.

[9] J.J. Manya, E. Velo, L. Puigjaner, Kinetics of biomass pyrolysis: a reformulated three-parallel-reactions model, Ind. Eng. Chem. Res. 42 (2003) 434–441.

[10] G. Varhegyi, M.J. Antal Jr., E. Jakab, P. Szabo, Kinetic modeling of biomass pyrolysis, J. Anal. Appl. Pyrolysis 42 (1997) 73–87.

[11] K. Raveendran, A. Ganesh, K.C. Khilart, Influence of mineral matter on biomass pyrolysis characteristics, Fuel 74 (1995) 1812–1822.

[12] P. Basu, Biomass Gasification and Pyrolysis Practical Design and Theory, Academic Press, Elsevier, USA, 2010.

[13] A. Demirbas, Current technologies for the thermo-conversion of biomass into fuels and chemicals, Energy Sources 26 (2004) 715–730.

[14] S. Kohli, M.R. Ravi, Biomass gasification for rural electrification: prospects and challenges, SESI J. 13 (2003) 83–101.

[15] B. Buragohain, P. Mahanta, V.S. Moholkar, Biomass gasification for decentralized power generation: the Indian perspective, Renew. Sustain. Energy Rev. 14 (2010) 73–92.

[16] Y.A. Lenis, A.F. Agudelo, J.F. Perez, Analysis of statistical repeatability of a fixed bed downdraft biomass gasification facility, Appl. Therm. Eng. 51 (2013) 1006–1016.

[17] M. Dogru, A. Midilli, G. Akay, C.R. Howarth, Gasification of leather residues-part I. Experimental study via a pilot scale air blown downdraft gasifier, Energy Sources 26 (2004) 35–44.

[18] D. Vera, B. de Mena, F. Jurado, G. Schories, Study of a downdraft gasifier and gas engine fueled with olive oil industry wastes, Appl. Therm. Eng. 51 (2013) 119–129.

[19] A.A.P. Susastriawan, Development of Technologies for Complete Utilization of Waste of Oil Seed Collections (M.Tech. thesis), Mechanical Engineering Department, Indian Institute of Technology Delhi, New Delhi (India), 2009.

[20] A.S. Ramadhas, S. Jayaraj, C. Muraleedharan, Dual fuel mode operation in diesel engines using renewable fuels: rubber seed oil and coir-pith producer gas, Renew. Energy 33 (2008) 2077–2083.

[21] T.B. Reed, A. Das, Handbook of Biomass Downdraft Gasifier Engine Systems, Solar Energy Research Institute, Colorado-80401, 1988.

[22] NETPRO Renewable Energy 20 kWe – Operational & Maintenance Manual, Micro model Complex, IIT, Delhi, India, 1999.

[23] A.K. Sharma, Modeling fluid and heat transport in the reactive, porous bed of downdraft (biomass) gasifier, Int. J. Heat Fluid Flow 28 (2007) 1518–1530.

[24] H. Yang, R. Yan, T. Chin, D.T. Liang, H. Chen, C. Zheng, Thermogravimetric analysis-Fourier transform infrared analysis of palm oil waste pyrolysis, Energy Fuels 18 (2004) 1814–1821.

[25] D.B. Parekh, Y.C. Rotliwala, P.A. Parikh, Synergetic pyrolysis of high density polyethylene and Jatropha and Karanja cakes: a thermogravimetric study, Renew. Sustain. Energy 1 (2009) 033107–033110.

[26] P. Murugan, N. Mahinpey, K.E. Johnson, M. Wilson, Kinetics of the pyrolysis of lignin using thermogravimetric and differential scanning calorimetry methods, Energy Fuels 22 (2008) 2720–2724.

[27] H. Wang, J. Yang, S. Long, X. Wang, Z. Yang, G. Li, Studies on the thermal degradation of poly (phenylene sulfide sulfone), Polym. Degrad. Stab. 83 (2004) 229–235.

[28] Y. Tonbul, Pyrolysis of pistachio shell as a biomass, J. Therm. Anal. Calorim. 91 (2) (2008) 641–647.

[29] E. Biagini, A. Fantei, L. Tognotti, Effect of the heating rate on the devolatilization of biomass residues, Thermochim. Acta 472 (2008) 55–63.

[30] R. Yin, R. Liu, J. Wu, X. Wu, C. Sun, C. Wu, Influence of particle size on performance of a pilot-scale fixed-bed gasification system, Bioresour. Technol. 119 (2012) 15–21.

[31] F.V. Tinaut, A. Melgar, A. Horrillo, A.D. Rosa, Method for predicting the performance of an internal combustion engine fuelled by producer gas and other low heating value gases, Fuel Proc. Tech. 87 (2006) 135–142.

[32] P.V.R. Iyer, T.R. Rao, P.D. Grover, Biomass-thermo Chemical Characteristic, third ed., Chemical Engineering Department, IIT, Delhi, 2002.